DEVELOPMENT OF TROPICAL CYCLONES IN RELATION TO CIRCULATION PATTERNS AT THE 200-MILLIBAR LEVEL*

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ABSTRACT

The 200-mb. flow existing above low-level perturbations at the time of development into tropical storm or hurricane intensity was studied. On the basis of observations in a sample of 40 cases, it is concluded that poleward flow aloft, such as is found in the eastern side of troughs in the westerlies and tropical upper-level cold Lows or in the western side of anticyclones, is more favorable for development of low-level perturbations underneath than equatorward flow. It is also shown that flow aloft with anticyclonic vorticity is more favorable than flow with cyclonic vorticity.

1. INTRODUCTION

It is generally accepted among practicing tropical meteorologists that tropical cyclones develop in some type of pre-existing perturbation at low levels and that an outflow mechanism at high levels over the surface depression is also a prerequisite for intensification (Riehl [10]). The requirement for upper-level divergence stems from the fact that an initial mass convergence at low levels would lead to a pressure rise in the center unless it was counterbalanced by a larger divergence aloft. A pressure fall at the surface would result only if the predominant mechanism is the divergent current at the upper levels. Various physical mechanisms by which the upper-level divergence can be initiated have been proposed by Sawyer [12], Kleinschmidt [6], Riehl [9], and Alaka [1].

Normally the tropospheric flow over the tropical latitudes consists of two main layers: the low-level trades in the lower 10,000 to 20,000 ft. and an upper layer with main activity centered near the 200-mb. level, which is characterized by a cellular structure of Highs and Lows traveling westward at a speed generally different than that of the low-level systems. Therefore, a low-level disturbance in the trades moving westward across the tropical Atlantic Ocean, Caribbean, and Gulf of Mexico may come under the influence of different types of circulation at the 200-mb. level ([13], pp. 25–28). A constant preoccupation of forecasters engaged in hurricane work is how to foresee when the low-level perturbation is going to come under the action of conditions aloft favorable for development and how to assess these conditions objectively. It is also generally accepted that conditions at high levels are not a sufficient factor and that the other properties of the low-level perturbation or the ambient atmosphere are also important.

During the course of daily map discussions conducted at the National Hurricane Center in Miami during the 1959 and 1960 hurricane seasons, it came to light that there was usually no unanimous agreement and no background experience to indicate what type of flow was really the most favorable for development. Because of the scarcity of data, it was seldom possible to make a reliable objective assessment of the properties of the flow in a given synoptic situation. As a result, the project described in this report was initiated to test the idea that certain identifiable patterns of flow at the 200-mb. level are more favorable than others, to determine these favorable patterns, and to see whether it would be possible to secure statistically meaningful data to back up the conclusions. Our aim was to get some preliminary results in a relatively short time so that they would be available for use as soon as possible. Therefore, the approach used was rather simple and straightforward. Use was made of the 200-mb. charts for the hurricane seasons 1956 to 1960 in file at the U.S. Fleet Weather Facility in Miami. For the 1961 and 1962 seasons the charts analyzed at the U.S. Weather Bureau, National Hurricane Center in Miami were used. The surface positions of each of the tropical cyclones, from their initial stages, were entered in the 200-mb. charts, together with some information on the

*The first draft of this report was written before the 1961 hurricane season, and the ideas developed were put to use during the 1961 and 1962 seasons. The statistics have been modified to include data through the 1962 season.

strength of the maximum winds, the direction of motion, and the trend of the changes in intensity. Then the wind direction at the 200-mb. level over the surface Low was determined from the synoptic analysis to eight cardinal points and tabulations were made. Other information on sign of the curvature of the flow and of the horizontal wind shear aloft was also noted in cases in which data were adequate for the purposes.

The results presented below pertain only to the conditions at the time of initial development. In some cases the systems developed rapidly to hurricane intensity; more frequently they developed to tropical storm intensity and later to hurricane strength. On occasions there were significant changes in intensity later on during the life cycle of the system; these were not considered.

A total of 40 cases was available in the seasons 1956–62 in which development occurred in areas where a reliable estimate of the flow aloft could be made. For convenience in discussion, these were subdivided into three major groups, according to the longitude of the area of formation; namely, the Antilles group (formations in the vicinity of the Lesser Antilles); the Bahamas-western Caribbean group (formations in the Bahamas area and the western Caribbean Sea), and the Gulf of Mexico group. Information in regard to the maximum intensity attained and the character of the flow at the time of development is tabulated in tables 1 to 3. The number of cases in each group is relatively small, but the statistical breakdown is quite encouraging.

2. DISCUSSION OF RESULTS

ANTILLES GROUP

A total of nine cases was available in the Antilles sample (tables 1, 4). There were other major hurricanes that developed in this area during the period of study, such as Donna of 1960, Cleo of 1958, Carrie of 1957, etc., but they were already of hurricane intensity at the time of detection, or the data were inadequate. Of the nine cases, eight developed under flow with southerly components, such as is found in the southwestern or western sides of anticyclones, or eastern sides of upper Lows. There was only one case of development that could be classified as occurring under flow with northerly components. This was the case of Anna (1961) which intensified rapidly in the vicinity of Trinidad at a time when the 200-mb. flow at that station was from the east-northeast. In all cases but one, the curvature was anticyclonic; in the few cases in which it was possible to determine the sign of the horizontal wind shear (information not tabulated), it was also anticyclonic.

A few examples of development in this area are shown in figures 1–4. In the Abby case (fig. 1) the flow at

TABLE 1.—*Wind flow at 200 mb. in the development stage of indicated storms, Antilles area*

Storm	Maximum intensity attained	Estimated wind flow at 200 mb. above surface center		
		Direction	Speed (kt.)	Curvature
1. Gerda (1958)	Storm	S	20	Anticyclonic.
2. Fifi (1958)	Weak hurricane	SE		Anticyclonic.
3. Ella (1958)	Weak hurricane	SE	15	Anticyclonic.
4. Hannah (1959)	Intense hurricane	SW		Anticyclonic.
5. Flora (1959)	Weak hurricane	SW		Cyclonic.
6. Edith (1959)	Storm	SE	10	Anticyclonic.
7. Abby (1960)	Weak hurricane	SE	20	Anticyclonic.
8. Anna (1961)	Moderate hurricane	NE	30	Anticyclonic.
9. Frances (1961)	Intense hurricane	SE		Anticyclonic.

TABLE 2.—*Wind flow at 200 mb. in the development stage of indicated storms, Bahamas-western Caribbean area*

Storm	Maximum intensity attained	Estimated wind flow at 200 mb. above surface center		
		Direction	Speed (kt.)	Curvature
1. Greta (1956)	Moderate hurricane	SW	35	Cyclonic.
2. Ethel (1956)	Storm	S	15	Anticyclonic.
3. Carla (1956)	Storm	SW		Cyclonic.
4. Frieda (1957)	Weak hurricane	N		Anticyclonic.
5. Janice (1958)	Moderate hurricane	SW	20	Anticyclonic.
6. Helene (1958)	Intense hurricane	E	20	Anticyclonic.
7. Daisy (1958)	Intense hurricane	E		Anticyclonic.
8. Gracie (1959)	Intense hurricane	SE	10–15	Anticyclonic.
9. Cindy (1959)	Weak hurricane	N		Anticyclonic.
10. Florence (1960)	Storm	NE	20	Zero.
11. Cleo (1960)	Weak hurricane	SW		Cyclonic.
12. Carla (1961)	Intense hurricane	SE	30	Anticyclonic.
13. Gerda (1961)	Storm	SW		Cyclonic.
14. Hattie (1961)	Intense hurricane	SE		Anticyclonic.
15. Alma (1962)	Storm	SW	10	Anticyclonic.
16. Ella (1962)	Moderate hurricane	SW	35	Anticyclonic.

TABLE 3.—*Wind flow at 200 mb. in the development stage of indicated storms, Gulf of Mexico*

Storm	Maximum intensity attained	Estimated wind flow at 200 mb. above surface center		
		Direction	Speed (kt.)	Curvature
1. Flossy (1956)	Weak hurricane	S		Anticyclonic.
2. Dora (1956)	Storm	E		Anticyclonic.
3. Anna (1956)	Weak hurricane	E		Anticyclonic.
4. Bertha (1957)	Storm	W		Anticyclonic.
5. Audrey (1957)	Intense hurricane	S		Zero.
6. Alma (1958)	Storm	E		Anticyclonic.
7. Unnamed system 8/25–26/59.	Intense depression	SE		Anticyclonic.
8. Judith (1959)	Weak hurricane	SW	20	Anticyclonic.
9. Irene (1959)	Storm	SW		Anticyclonic.
10. Debra (1959)	Weak hurricane	E	20	Anticyclonic.
11. Beulah (1959)	Weak hurricane	SW	25	Zero.
12. Arlene (1959)	Storm	S	30	Zero.
13. Ethel (1960)	Moderate hurricane	SW		Anticyclonic.
14. Brenda (1960)	Storm	N		Anticyclonic.
15. Inga (1961)	Storm	SW		Anticyclonic.

TABLE 4.—*Frequency distribution of cases of development with respect to the wind circulation at 200 mb.*

Wind flow at 200 mb.	Antilles area	Bahamas-western Caribbean area	Gulf of Mexico area	Total
N		2	1	3
NE	1	1		2
E		2	4	6
SE	5	3	1	9
S	1	1	3	5
SW	2	7	5	14
W			1	1
NW				0
Total	9	16	15	40

200 mb. shows a cyclone centered just north of Puerto Rico, with an anticyclone to the east and a weak ridge extending east-west across the eastern Caribbean. The wind flow over the Leeward Islands was from the south; at Trinidad it was east-southeast. The surface perturbation was located near 13° N., 56° W. with maximum winds of 26 kt. The flow directly above was estimated as southeast with anticyclonic curvature. Twelve hours later (fig. 2), the maximum winds had increased to about 46 kt. (tropical storm intensity) as the flow over the low-level system became slightly more southerly. In another 12 hr. (chart not shown), the surface winds of Abby had increased to 64 kt.

Figure 3 illustrates the case of tropical storm Edith of 1959, at the time the maximum winds were around 16 kt. The flow above the perturbation was estimated as southeasterly, although it might be more like east-southeasterly. The storm moved across the Lesser Antilles during the 18th with tropical storm intensity. It never reached much strength and, eventually, dissipated south of the Mona Passage.

Another example of development under southerly flow is shown in figure 4, which shows the position of the surface perturbation of hurricane Ella of 1958 at the time it was located under a fairly strong anticyclonic current. The maximum winds at the surface at this time were about 30 kt. During the next 24 hr. they intensified to around 60 kt.

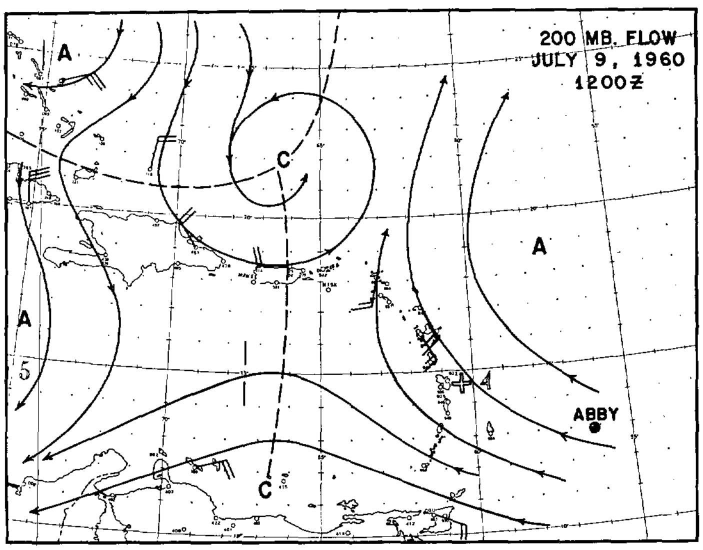

FIGURE 1.—200-mb. flow above the developing hurricane Abby.

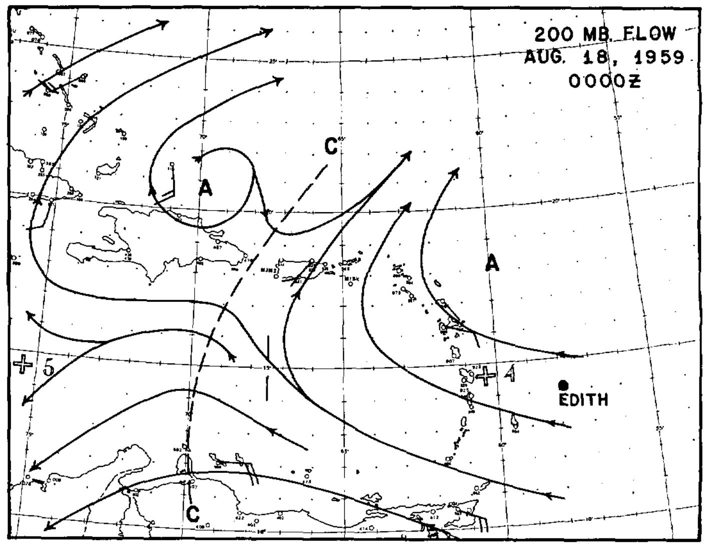

FIGURE 3.—200-mb. flow above tropical storm Edith when its maximum surface winds were around 16 kt.

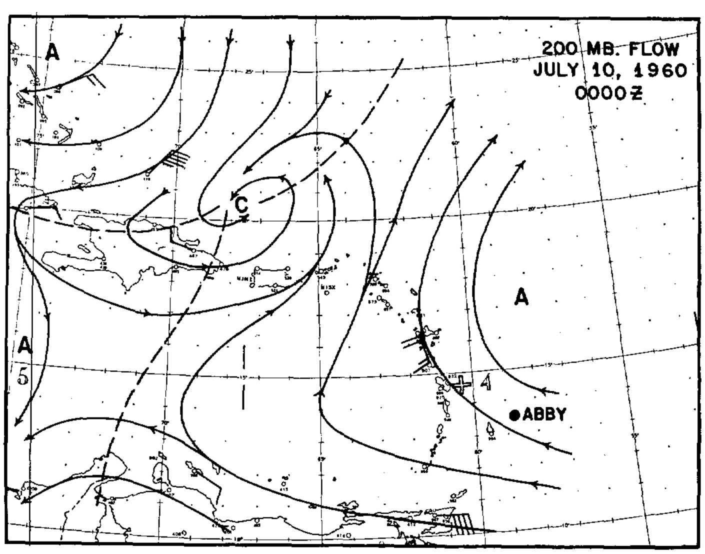

FIGURE 2.—200-mb. flow 12 hours later than figure 1.

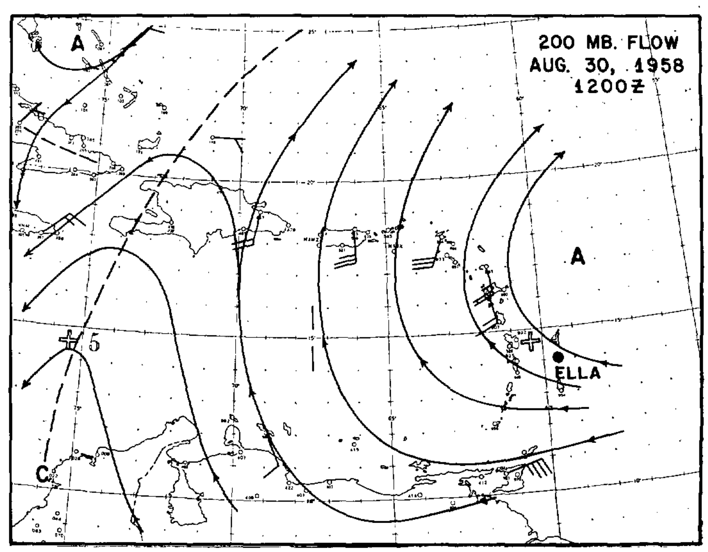

FIGURE 4.—Location of hurricane Ella in relation to 200-mb. flow when Ella's maximum surface winds were about 30 kt.

BAHAMAS-WESTERN-CARIBBEAN GROUP

The developments in this group presented more variety of circulation patterns aloft. Several cases developed in association with troughs in the westerlies. In other cases, like Daisy and Helene of 1958 and Cindy of 1959, there were large variations in the upper flow during the period of development, so that it is somewhat difficult to decide the type of circulation that was most decisive in triggering the intensification. Of a total of 16 cases (tables 2, 4) there were 11 cases of development with southerly flow aloft; 7 with southwesterly, 1 with southerly, and 3 with southeasterly winds; 3 cases with northerly flow; and 2 cases with easterly flow. There were 4 cases in which the southwesterly flow aloft had cyclonic curvature. Several examples of the 200-mb. flow patterns associated with developments in this area are shown in figures 5–10.

Figures 5 and 6 show the conditions at the time of the intensification of hurricane Cleo of 1960. At 1200 GMT, on August 17, 1960 (fig. 5), the surface perturbation was located under westerly flow aloft. The maximum winds at the surface were about 15–20 kt. With the establishment of the trough in the westerlies near Florida, the flow over the surface perturbation changed to southwesterly in the next 12 hr. and by 1200 GMT on August 18, 1960 (fig. 6) the surface winds had intensified to around 60 kt. The curvature of the flow appeared to be slightly cyclonic.

Two other examples of development under southwesterly flow are shown in figures 7 and 8. At 1200 GMT on October 5, 1958 (fig. 7), the disturbance that developed into hurricane Janice was located south of Cuba with maximum surface winds of about 32 kt.; it was located under southwesterly flow aloft ahead of a trough moving from the west. During the next 24 hr. the maximum winds in-

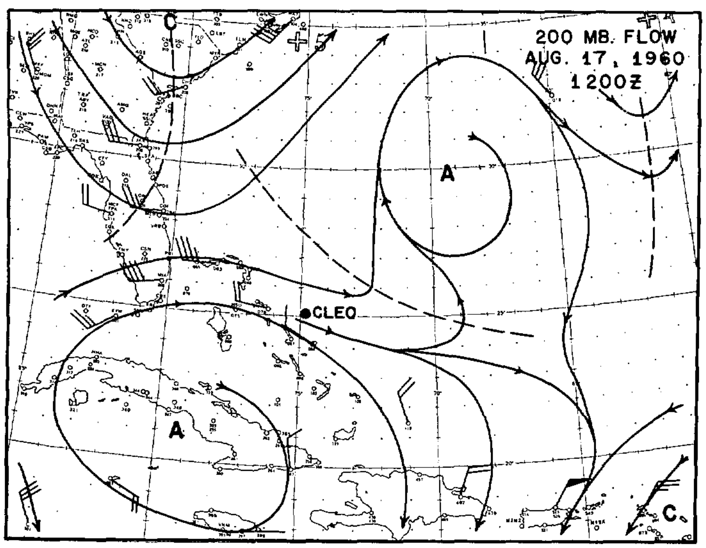

FIGURE 5.—200-mb. flow at time of intensification of hurricane Cleo.

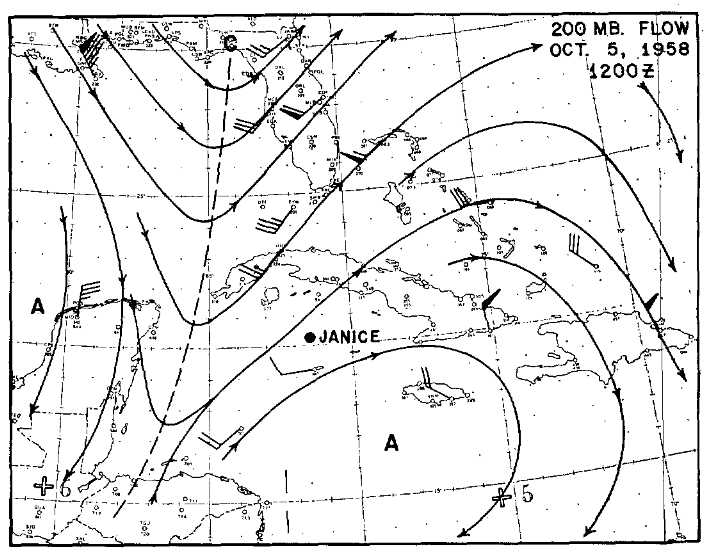

FIGURE 7.—200-mb. flow above developing hurricane Janice.

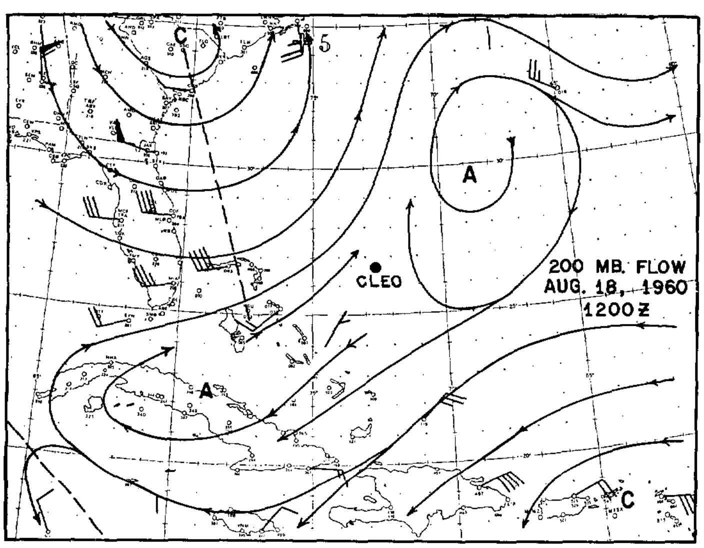

FIGURE 6.—200-mb. flow above hurricane Cleo 24 hours after figure 5. By this time surface winds in Cleo had reached 60 kt.

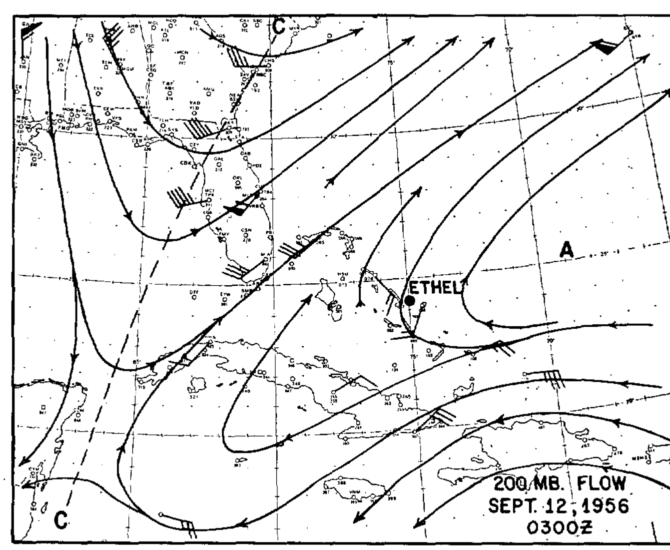

FIGURE 8.—200-mb. flow over tropical storm Ethel when its surface winds were around 25 kt.

creased to around 50–55 kt. in spite of the motion across Cuba, as the flow aloft became more southerly and quite strong (speeds of 40–50 kt.). Janice reached hurricane intensity on the evening of October 6. Figure 8 illustrates the position of tropical storm Ethel of 1956 when the surface winds were around 25 kt. It was then located under southerly flow on the west side of an anticyclone and ahead of a trough moving in from the west. On the afternoon of September 12, the system intensified to a tropical storm with maximum winds of 60–65 kt. Ethel moved northeastward and rapidly assumed extratropical characteristics.

Figures 9 and 10 show the conditions associated with the development of hurricane Cindy of 1959. This case was classified as under northerly flow, in table 2, since the flow aloft was northerly at the time the development period started, but the development appears to have been

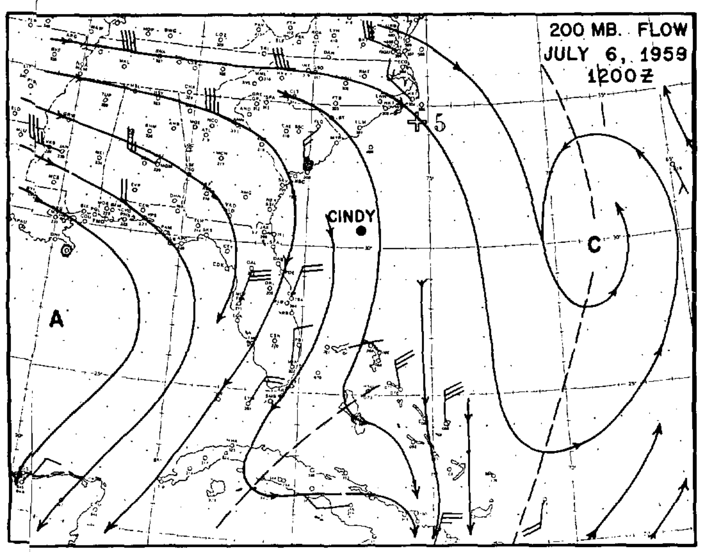

FIGURE 9.—200-mb. flow above perturbation which developed into hurricane Cindy. Note northerly flow at this time.

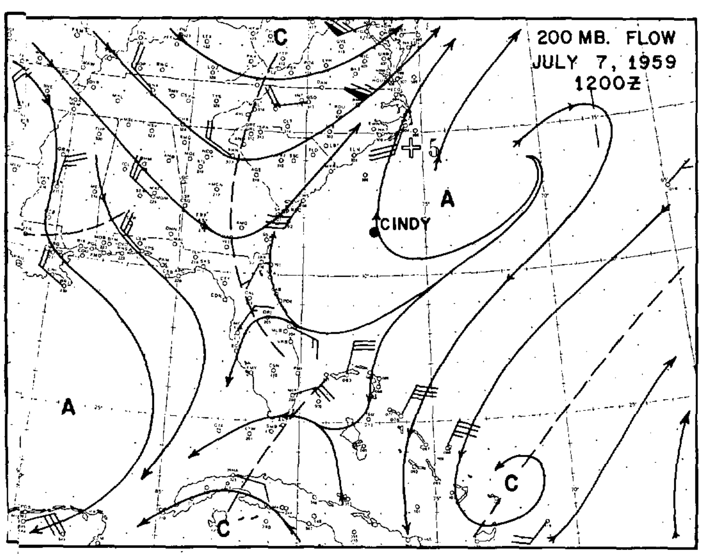

FIGURE 10.—200-mb. flow above Cindy 24 hours after figure 9. Cindy became a weak hurricane in the next 24 hours.

triggered by a reversal in the wind flow. At 1200 GMT on July 6, 1959 (fig. 9), the perturbation was located near 31° N., 77° W., with maximum winds of around 30 kt. At the 200-mb. level there was a Low to the east near Bermuda, a northeast-southwest ridge line along the east coast, and a trough in the westerlies farther west. The surface depression was then located under the northerly flow west of the Bermuda Low. During the next 24 hr. there was a significant change in the circulation above the surface Low. There was a strong development and eastward motion of the ridge and of the westerly trough, and very little motion of the surface depression, so that the flow above changed from northerly to southerly. At 1200 GMT on July 7 (fig. 10) the intensity of the surface winds had increased to around 55 kt., as the surface Low moved to the west side of the ridge line. Cindy reached weak hurricane intensity and eventually moved inland on the Carolina coasts on July 8.

GULF OF MEXICO

The development of storms in the Gulf of Mexico was also largely associated with troughs in the westerlies. Of 15 cases investigated (tables 3, 4), 9 formed under southerly flow aloft ahead of westerly troughs (see figs. 11–13); 4 developed under the easterly flow in the south side of anticyclones; 1 system formed under westerly flow; and 1 formed under northerly flow. Three of the cases of formation with easterly flow aloft were located in the extreme southwestern corner of the Gulf and one near the Texas coast; the cases of westerly and northerly winds occurred in the northern and northeastern sections, respectively. Of the cases classified under easterly flow, there were some (see figs. 14–15) in which development started in the southern side of the anticyclone and intensification proceeded as the surface system moved westward toward the southwestern quadrant of the upper cell. Some examples of formations in the Gulf area are illustrated in figures 11–15.

Figure 11 shows the situation at 0000 GMT on September 14, 1960, when the surface depression that developed into hurricane Ethel was located in the southern Gulf with maximum surface winds of around 20 kt. At the 200-mb. level the perturbation appeared under the southwesterly flow to the east of an approaching trough in the westerlies. During September 14, Ethel moved northeastward and intensified explosively into hurricane intensity (Dunn [4]). Figures 12 and 13 show a somewhat similar case—hurricane Audrey of 1957. At 0000 GMT on June 25, 1957 (fig. 12), the perturbation of Audrey was located in the southern Gulf with winds of about 30 kt. At the 200-mb. level the flow was from the south in a position just west of a small anticyclone centered in the Yucatan Peninsula and to the east of a rather pronounced trough in the westerlies. During the following 24 hr. the trough over Mexico retrograded, the southerly flow aloft over the western Gulf persisted with rather high speeds, and the surface perturbation moved northward and intensified rapidly to hurricane intensity. At 0000 GMT on June 26 (fig. 13), Audrey

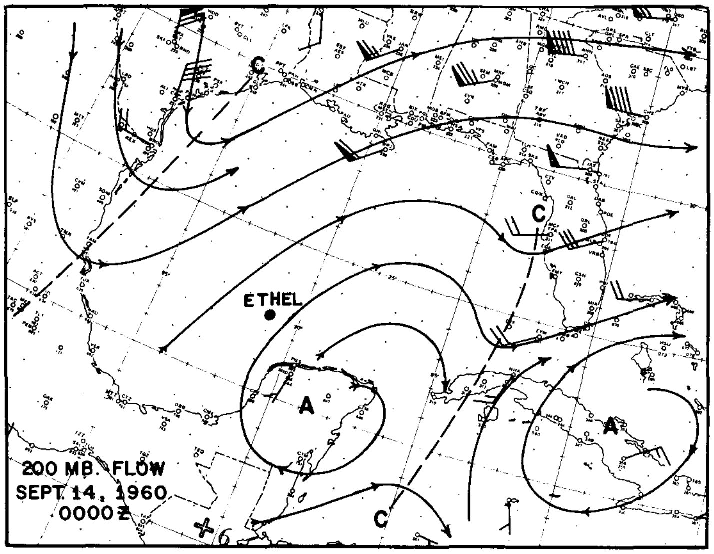

FIGURE 11.—200-mb. flow above developing hurricane Ethel.

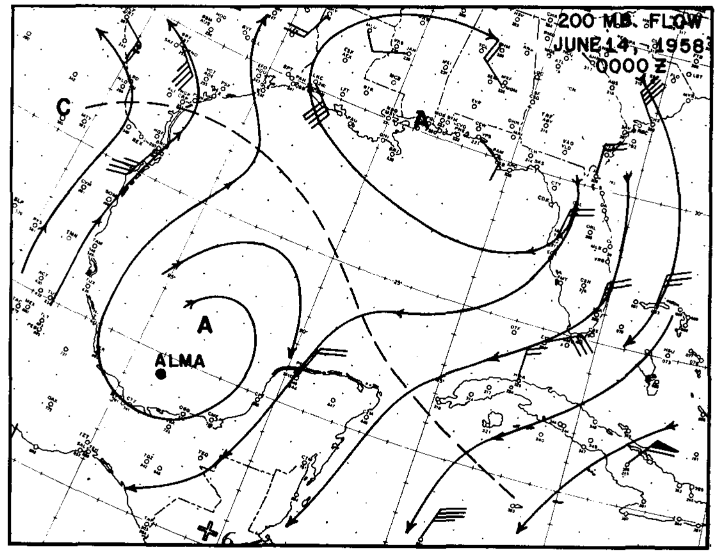

FIGURE 14.—200-mb. flow above developing tropical storm Alma.

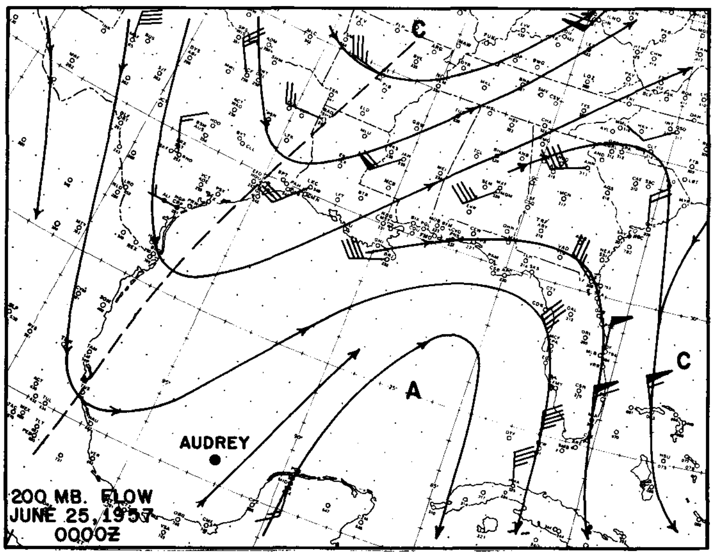

FIGURE 12.—200-mb. flow at time Audrey had surface winds around 30 kt.

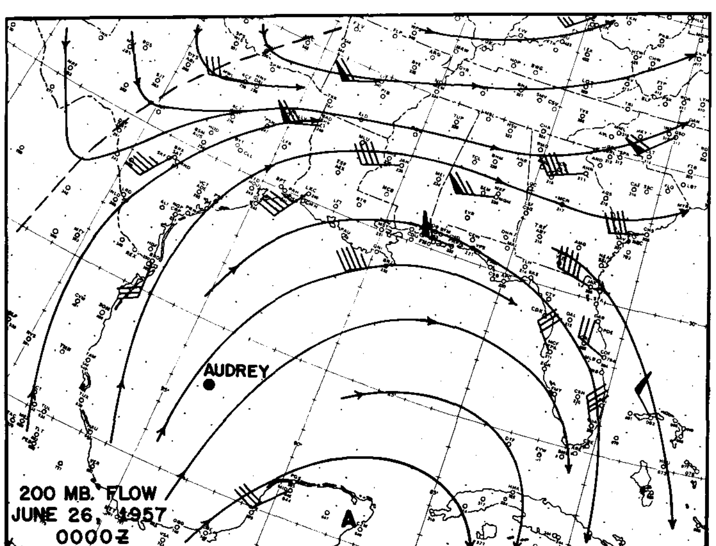

FIGURE 13.—200-mb. flow 24 hours after that of figure 12. Audrey's surface winds have strenthened to about 90 kt.

was located in the central Gulf, with winds of about 90 kt., and under southerly flow aloft. Further deepening occurred before the hurricane went inland on the Louisiana coast.

Figures 14 and 15 illustrate the formation of tropical storm Alma of 1958 as it moved from the southern to the southwestern side of an anticyclone in the southern Gulf. At 0000 GMT on June 14, 1958 (fig. 14), the perturbation was located in the southern Gulf under the southern edge of the anticyclone. The flow above the perturbation was estimated as easterly. During this day the surface Low moved northwestward as the upper anticyclone intensified, and deepening to tropical storm intensity took place. The next day (fig. 15) Alma had maximum winds of 45 kt. and was located under the southwestern quadrant of the upper-level cell. This storm moved into Mexico before it had opportunity for further development.

3. CONCLUSIONS AND CLOSING REMARKS

As stated initially, the main purpose in this study was to see whether there were recognizable patterns of flow at the 200-mb. level favorable for development of surface perturbations underneath. This has been established well, even with the relatively small sample of storms studied. Of a total of 40 storms (table 4), there were 28 cases of development when the perturbation was located under the southerly flow in the western side of upper anticyclones or eastern side of troughs, as compared to 5 cases of formation underneath the eastern half of anticyclones. Even in some cases in which the upper flow at the beginning of the development period was classified as northerly (or as easterly) there were indications that the decisive factor in triggering intensification was a change to the more favorable flow with southerly components (see the case of Cindy, 1959, figs. 9–10). It

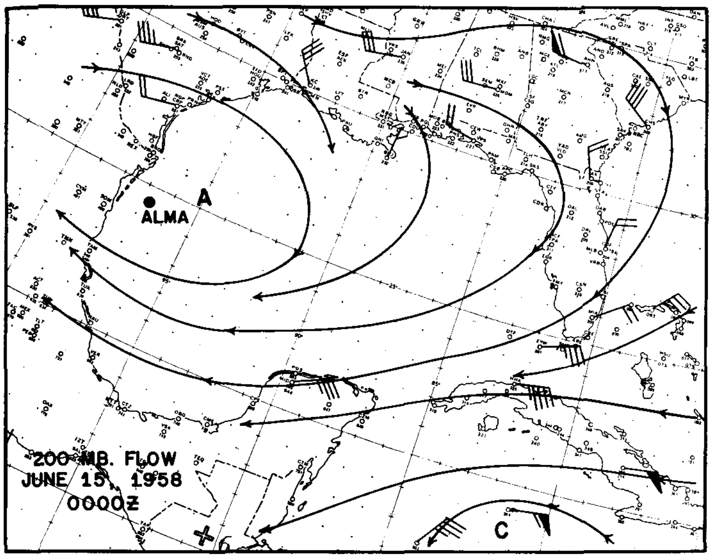

FIGURE 15.—200-mb. flow 24 hours after that of figure 14.

was shown also that anticyclonic curvature and shear aloft were favorable for development.

In the vicinity of the Lesser Antilles the favorable type of flow was generally found east of upper cold Lows or ahead of anticyclones that moved westward in the tropical current. Formations in the Bahamas Islands and in the Gulf of Mexico were frequently associated with tropical extensions of troughs in the westerlies. However, developments related to tropical cyclonic and anticyclonic cells were also observed in the western areas.

The fact that poleward flow at the 200-mb. level tends to be favorable for hurricane development, has been noted in the literature (Miller [7], Ramage [8]). The composite charts of 200-mb. flow for weak and intense hurricanes, prepared by Miller [7], show definitely the presence of the anticyclone to the east and trough to the northwest of the hurricane center. His charts, however, were for cases of existing hurricanes and there is a question as to what extent they represent conditions at the time of development. After a study of examples published in the literature, Ramage [8] arrived at the qualified statement that poleward flow was favorable in cases of development in the equatorward side of the subtropical ridge line. Our results indicate that the observation is generally true in all regions. Riehl et al. [11] conducted a study of formations in the Gulf of Mexico and arrived at results concerning the upper flow similar to ours.

There are two questions to be considered in connection with the statistical results discussed above and which affect the value of the conclusions. One concerns the nondevelopment cases; i.e., the frequency of potentially unstable perturbations which were located under southerly flow aloft and did not develop. The other question is related to a possible bias in the association between low-level and high-level perturbations and can be stated in the following manner: are the results in table 4 merely a reflection of the fact that *all* low-level perturbations occur in association with southerly flow at 200 mb?

This second question has a direct and fundamental effect on the value of the statistics discussed above and efforts were made to elucidate the matter. A tabulation was made of the character of the flow at the 200-mb. level associated with all perturbations detected over the data network during the 1959 through 1962 seasons (period June to October). The tabulation was done every 12 hr. (every upper-air map) throughout the life span of the perturbations. A total of about 70 different perturbations studied in this manner yielded a total of 286 observations. It was found that in about 54 percent of the observations, the flow over the low-level perturbation had southerly components, as compared to 27 percent with northerly components. Thus it seems that there is some bias in the association between low-level and upper-level perturbations and that there is a two to one chance that the upper flow over a given perturbation in the easterlies is from a southerly, in contrast to a northerly, direction. On the other hand the statistics on conditions at the time of development indicate about a 5 to 1 likelihood that storm formation occurs in association with southerly, in contrast to northerly, flow aloft. It appears, then, that the results point to a meaningful relationship between conditions in the lower and upper troposphere at the time of tropical storm genesis.

The question concerning nondeveloping perturbations, which bears on the sufficiency of the conditions at high levels, is more difficult to answer. First, it is not easy to assess objectively the potential for development of perturbations that fail to intensify; and second, one never knows with certainty which conditions, by either their presence or absence, were instrumental in preventing development. No attempt was made to go over the material for the period of study and investigate this feature. Some attention was given to it during the course of the daily weather analysis at the National Hurricane Center in the 1961 and 1962 hurricane seasons, but it was not possible to arrive at any meaningful statistical results.

The fundamental questions to be considered next are what is the property of the upper-level flow patterns that has a bearing on storm development and what is the physical mechanism involved? No attempt was made in this project to go into this problem. One can note, however, that anticyclonic curvature and shear of the 200-mb. flow seem to have a bearing on the problem. This gives some weight to the physical mechanism which invokes the existence of dynamic instability at upper levels [1, 2, 9]. Alaka [2, 3] has made a more thorough analysis of the properties of the 200-mb. flow in the cases of hurricanes Gracie (1959) and Carla (1961) and detected conditions in support of his ideas on hurricane genesis. One can also recognize that the results, particularly in the region of the Gulf of Mexico and Bahamas area, confirm the well known rule on development on the eastern side of upper troughs that has been known to hold for cyclogenesis in middle latitudes.

In closing this discussion, we would like to add that in most of the situations investigated the patterns of flow at the 200-mb. level seem to have been determined by synoptic considerations independent of the presence or effect of the low-level perturbations. However, in recent seasons, situations have been observed in which anticyclogenesis and pronounced warming in the upper troposphere on a scale large enough to affect the synoptic patterns of flow at the 200-mb. level seem to have resulted from the effect of convective activity associated with unstable low-level perturbations. The flow patterns aloft and the low-level perturbation then became aligned in the manner found to be conducive to further intensification. Thus, some developing storms helped in creating their own outflow mechanism aloft. One such situation observed in September 1961 was studied by Frank [5]; others occurred in association with hurricanes Daisy and Ella of 1962, and will be the subject of further scrutiny in the future.

From the analysis described above, it can be safely concluded that evaluation of cyclogenesis in the Tropics in relation to circulation patterns at the 200-mb. level appears as a promising line of research, which warrants thorough and conscientious attention.

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